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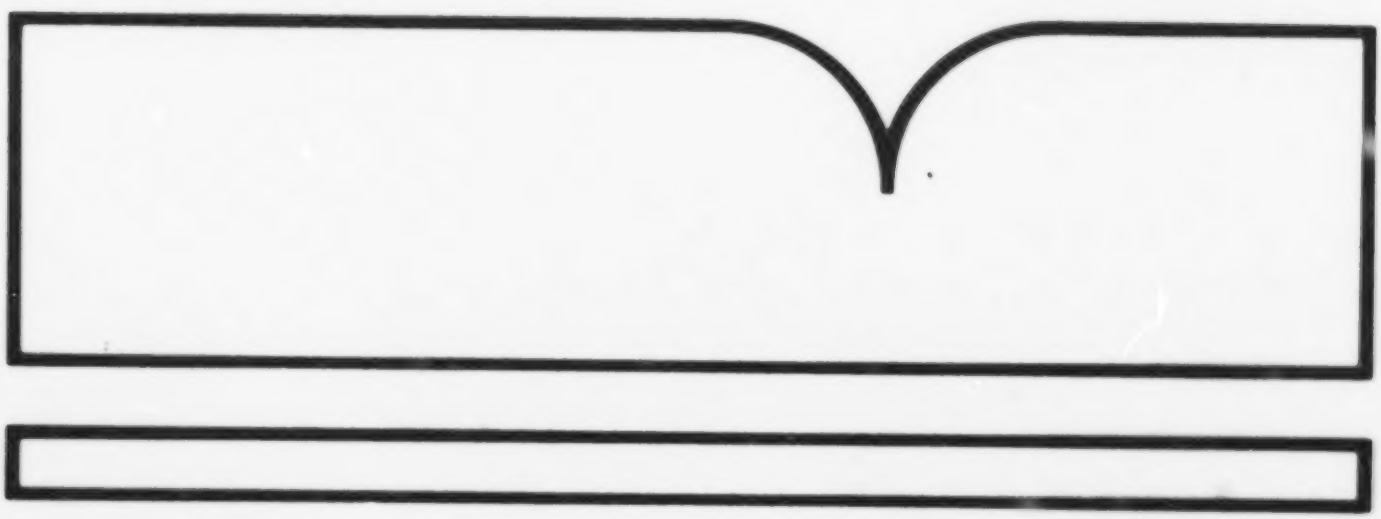

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16. ABSTRACT

Full-scale performance and costs of an innovative sludge stabilization process were evaluated at the three plants. The DDS incorporates a 1-day-detention-time, pure-oxygen aerobic digester followed in series by an 8-day-detention-time anaerobic digester. Heat of biological oxidation is conserved in the aerobic step; additional heat input is not required for the anaerobic step. The biogas generated by anaerobic digestion is usable elsewhere to help offset oxygen costs. Aerobic operation can be either mesophilic or thermophilic. Process operation, reliability, solids reduction, and capital and operating costs were evaluated.

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Technology evaluation of the dual digestion system

A. Ron Appleton, Jr., Albert D. Venosa

This paper discusses the results of a full-scale study of performance and costs of the dual digestion system (DDS). The DDS is an innovative sludge stabilization process that incorporates a 1-day detention time, pure-oxygen aerobic digester (Step I) followed by an 8-day detention time anaerobic digester (Step II). The heat generated through biological oxidation of the sludge in Step I is conserved so that mesophilic or thermophilic temperatures can be achieved in the aerobic step by controlling the pure-oxygen feedrate. No additional sludge heating is required in the anaerobic step, so the biogas generated is available for use elsewhere in the treatment plant.

Several sludge stabilization processes have been specifically listed in two categories by the U. S. Environmental Protection Agency (EPA) to produce a sludge acceptable for land application. Sludge treated by processes to significantly reduce pathogens (PSRP) (for example, anaerobic digestion for 15 days at temperatures between 35°C and 50°C with at least 38% volatile solids reduction) is acceptable for land application provided that public access is controlled for at least 12 months, grazing by animals whose products are consumed by humans is prevented for at least 1 month, and food crops for direct human consumption in which the sludge contacts the edible portion of the plant are not grown within 18 months. Sludge applied to food crops within 18 months, when the edible portion of the plant is contacted, is required to be treated by processes to further reduce pathogens (PFRP) (for example, static pile composting for at least 3 days at greater than 55°C). The other two restrictions on access and grazing also apply to sludge treated by a PFRP.[1] As a more recent technology, DDS is not included among the specifically listed PSRPs and PFRPs. One goal of this study was to document the volatile solids reduction and degree of pathogen destruction by DDS relative to the criteria for PSRPs and PFRPs. The effectiveness of DDS in pathogen destruction is detailed elsewhere.[2]

Based on the solids reductions achieved, the system might qualify for an EPA classification that allows more options for ultimate sludge disposal.

This project was part of the Innovative/Alternative Technology evaluation program of EPA. The project was comprised of two parts, a post-construction evaluation and a special performance study. The post-construction evaluation included site visits to all municipal wastewater treatment facilities that use this technology to collect available operating and cost data. The special study was designed to evaluate the performance of DDS at one of the facilities, with a focus on the degree of pathogen destruction. This aspect of DDS performance was important because the options for ultimate disposal of the stabilized sludge depend on the health risks posed by pathogenic organisms. The overall goal of this project was to verify the full-scale performance claims of this technology.

POST-CONSTRUCTION EVALUATION

Full-scale DDS facilities for sludge stabilization are operating at three treatment plants in the U. S. Three more systems are currently being constructed. The process was developed in the late 1970s.[3,4] Bench- and pilot-scale testing of DDS indicated that autoheating of the sludge from biological respiration was feasible and that solids destruction was comparable to conventional biological solids stabilization processes. The technology was demonstrated at full-scale at the Hagerstown Wastewater Treatment Plant (Hagerstown, Md.) in 1980.[5] Since then, systems have been installed at Nutbush Creek Wastewater Treatment Plant (Henderson, N. C.) and Lackawanna Sewage Treatment Plant (Lackawanna, N. Y.). A second aerobic reactor has been added to the DDS at Hagerstown as part of an overall plant expansion.

In the spring of 1984, initial site visits were made to the treatment plants in Hagerstown, Henderson, and Lackawanna. Discussions were held with plant personnel, the design engineers, and state regulatory agencies. Relevant design and operating data for each plant are listed in Table 1.

There are a number of process similarities among the three treatment plants. First, all the plants formerly used conventional, two-stage anaerobic digestion for sludge stabilization. At all the plants, the DDS aerobic step was retrofit into the existing sludge treatment scheme using the existing anaerobic facilities. Second, all the plants were modified to use pure-oxygen activated sludge in their secondary treatment train. The oxygen is supplied from a pressure swing adsorption (PSA) oxygen generation system, with a liquid oxygen backup. To meet the additional oxygen requirements of the Step I digester, an increment of PSA capacity above that required for secondary treatment was added. The PSA system capacities listed in Table 1 include the requirements of both pure-oxygen activated sludge and DDS. For Hagerstown, the PSA capacity listed also includes the oxygen used to generate ozone for final effluent disinfection.

Figure 1 shows how the existing two-stage anaerobic digesters were used in the DDS at Lackawanna. Process modifications to incorporate DDS were similar at the other two treatment plants. The reactor in the foreground is the Step I digester, constructed as part of the plant modification and expansion. The reactor in

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Table 1—Treatment plant summaries.

	Lackawanna	Hagerstown	Nutbush Creek
Basis of Innovative/Alternative Technology Funding Approval	Reliability	Cost and energy	Environmental benefits and reliability
DDS startup date	February 1983	June 1980, May 1984 (second unit)	December 1982
Average daily wastewater flow (design average/peak, m^3/s)	0.20/0.30	0.35/0.53	0.18/0.37
Secondary treatment process	Oxygen activated sludge	Oxygen activated sludge	Oxygen activated sludge (for nitrification)
PSA system capacity (kg/d)	2210	12 650	4410
Solids type	Primary and secondary	Primary, secondary, cheese whey, septage	Primary, trickling filter, nitrification
Solids thickening process	Gravity	Dissolved air flotation	Dissolved air flotation
DDS feed mode	Continuous	Intermittent	Intermittent
DDS design detention time (Step I/Step II, d)	1.17/7.4	0.9/12.0	1.25/10.4
Solids dewatering process	Centrifuge and/or drying bed	Plate-and-frame filter press	Drying beds
Ultimate sludge disposal	Landfill	Farmland	Landfill
Biogas use	Gas engine for PSA compressor for building heat	Scrubber and compressor vehicle fueling system	Gas engine for PSA compressor

the middle is Step II of DDS, formerly the first-stage digester. Because its original volume would yield too long a residence time for the anaerobic DDS step based on projected sludge volumes and increase heat loss, a smaller reactor was constructed within the old digester as illustrated in the process schematic shown in Figure 2. DDS at the other two treatment plants used the full volume of the former first-stage digester without modification. The former second-stage digester is in the background of Figure 1, and is used in DDS at the three plants to provide additional anaerobic digestion and solid/solution separation. This digester is informally called the Step III digester, although it would not be part of a totally new facility. A floating cover was added to this third digester at each plant during modification to provide storage for the biogas generated in the Step II and Step III digesters.

Figure 1—Dual digestion system at Lackawanna.

As shown in Table 1, DDS at the three plants was approved for a higher percentage of federal funding under the Innovative/Alternative Technology program for different combinations of the following criteria: reliability, cost, energy, and environmental benefits. The three treatment plants also differ in the types of sludge treated, thickening and dewatering processes used, method of ultimate disposal, and biogas utilization. A combination of primary and pure-oxygen secondary sludge is treated at Lackawanna and Hagerstown; and a combination of primary, trickling filter, and pure-oxygen nitrification sludge at Nutbush Creek. In addition, the Hagerstown DDS system is sized to receive supplemental biodegradable solids (cheese whey, septage) from outside the treatment plant to generate additional biogas. The DDS at Lackawanna is fed continuously from a gravity thickener. The DDS at the other two plants uses intermittent feeding from a dissolved air flotation thickener. At Lackawanna, a centrifuge or drying bed is used as the primary means of solids dewatering with a vacuum filter available for backup. At Hagerstown, a plate-and-frame filter press is used for dewatering; drying beds are used at Nutbush Creek.

Although a high degree of pathogen destruction is claimed for DDS, only Hagerstown uses agricultural land application for

ultimate sludge disposal. Sludge at the other two plants is disposed of in a landfill. The treatment plants also differ in their use of the biogas generated in the anaerobic step. A dual drive is installed for the PSA compressor at Lackawanna and Nutbush Creek. When sufficient biogas is available under the floating digester cover, a gas engine provides the driving force; otherwise, an electric motor is used. At Lackawanna, the biogas can also be used to heat the buildings during the winter. At Hagerstown, the biogas passes through a scrubber and is planned to be used in a vehicle fueling system.

In addition to general information about the DDS at each of the three plants, detailed operating data and, where available, cost information were collected. There was insufficient operating data available from Nutbush Creek to warrant its inclusion in further phases of this study. At Hagerstown, plant and digester operating summaries were routinely prepared and used to evaluate DDS performance. Operating data for conventional parameters were collected as part of the special study of pathogen destruction at Lackawanna.

DATA COLLECTION

Lackawanna. A residence time distribution study was conducted at Lackawanna to determine the mixing regime in the Step I digester. Lithium chloride (LiCl) was used as a conservative tracer in the sludge. The concentrated LiCl solution was poured into the chamber of the sludge diaphragm pump upstream of the Step I digester shown in Figure 2. Sludge samples were collected at the telescoping value downstream of the Step I digester at predetermined times and filtered to remove solids. Approximately 20 mL of the filtrate was acidified with concentrated HNO_3 and stored in plastic bottles at 4°C in the plant laboratory. After the sampling was complete, the bottles were packed in ice and shipped by overnight courier to a commercial laboratory. Samples were analyzed for lithium by atomic absorption spectrophotometry (Method 317A, "Standard Methods"[6]).

Three 10-week sampling periods were used for the special study at Lackawanna to adequately characterize pathogen destruction. These periods are referred to as Phase 1 (July 3–September 10, 1984), Phase 2 (September 19–December 7, 1984), and Phase 3 (February 13–April 24, 1985). Phase 1 is further broken down into Phase 1A and 1B. Because wastewater flows and solids production were less than design values, additional thickened sludge from a nearby wastewater treatment plant was imported for a 3-week period (August 8–22) referred to as Phase 1B. The remaining 7 weeks are referred to as Phase 1A. During these periods, plant operators collected daily performance and operating data. Two other sample locations were used in addition to the Step I effluent sampling site. The Step I influent was sampled from the sludge line downstream of the sludge diaphragm pump, and the Step II effluent was sampled from the sludge line between the Step II and Step III digesters.

Because of the daily variation in sludge stream solids concentration, the plant operators collected a grab sample once each 8-hour shift to make a daily composite. The composite sample was analyzed in the plant laboratory following Method 209F for total solids and total volatile solids, Method 423 for pH, and Method 403 for alkalinity in "Standard Methods."[6]

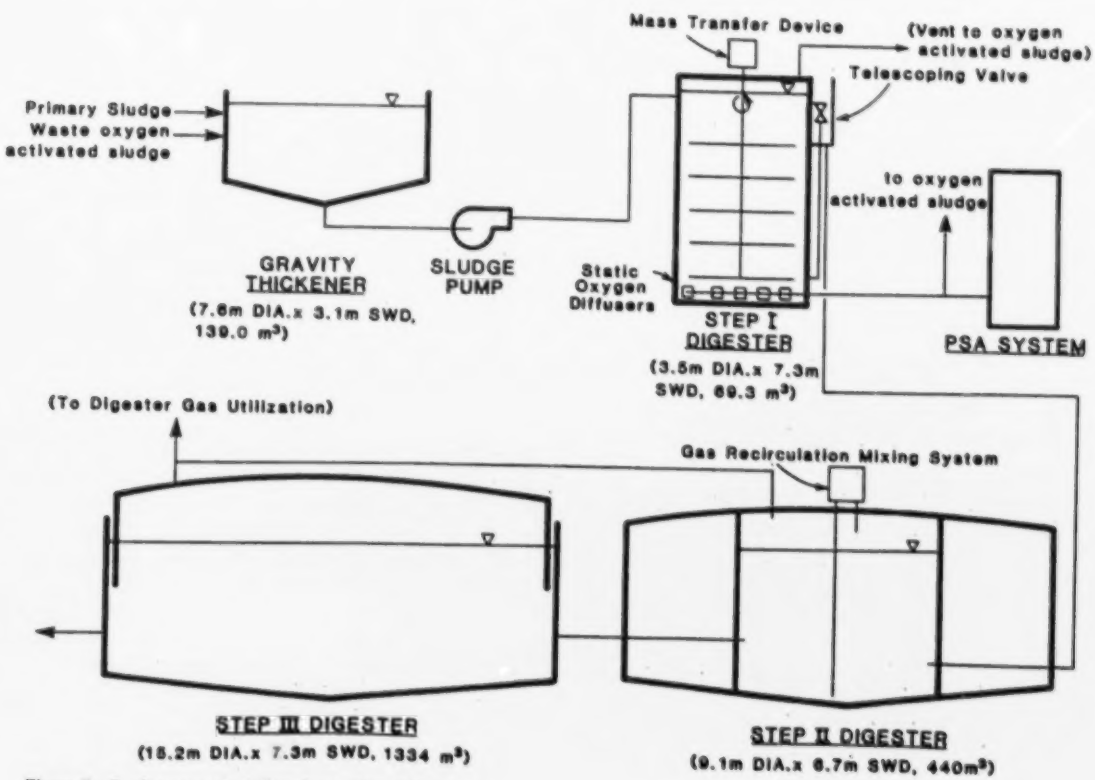

Figure 2—Lackawanna dual digestion system schematic.

To verify that a composite made from equal volumes of the three daily grab samples was representative of total solids, the total solids measured using the composite sample and the total solids measured by integration of continuous measurements of the sludge density were compared. The signal from a nuclear density meter just downstream of the sludge diaphragm pump was recorded on a strip chart in the plant control room. Four weeks of data was visually integrated to obtain an average daily total solids concentration. While the total solids concentration measured by the composite sample differed from the integrated value by as much as ±10%, the averages of the two measurements differed by only several percent for the 4-week period. Because the solids balance was to be analyzed over the 10-week sampling period, the total solids measured in the daily composite was considered representative.

Relevant operating parameters were recorded on standardized forms once each shift by plant operators. Sludge temperature at each sampling site was measured with a thermometer each morning at approximately 10 a.m. Sludge flowrates were measured using available instrumentation. The flowrate of the raw sludge to the Step I digester was measured using the number of strokes and chamber volume of the diaphragm pump. Early in the study, the stroke volume was directly measured by comparing the number of strokes per unit time against the measured drawdown in the upstream gravity thickener. Sludge flowed between the Step I and Step II digesters by gravity and was pumped from the Step II digester to the Step III digester. Sludge flow through the Step II digester was steady-state over the 10-week sampling periods.

A totalizer was used to calculate the daily gas production volume. During Phases 1A and 1B the totalizer was isolated so that only gas production in the Step II digester was measured. During Phases 2 and 3, the gas meter measured production in both Step II and Step III.

Hagerstown. Available operating and performance data were obtained from Hagerstown between September 1983 and August 1984. Daily operations reports summarized DDS pumping rates and digester temperatures. Digester reports generated three times each week listed digester pH, alkalinity, volatile acids, gas production, and total and volatile solids based on grab sample analyses. The data were separated into two phases as a result of construction of the second Step I digester, which was put on-line on May 30, 1984. Before this date, there was one DDS process train, similar to that shown in the schematic of Figure 2. Sludge was fed every hour to the Step I digester to achieve a 1-day detention time. Sludge then flowed by gravity to the Step II digester, and then to the Step III digester. The other two anaerobic digesters not used for DDS were operated as conventional, two-stage anaerobic digesters before May 30, 1984. After the second Step I digester was on-line, two parallel DDS process trains were operated; the raw sludge pump alternately fed the two Step I digesters.

PERFORMANCE EVALUATION

The results of the Step I residence time distribution study at Lackawanna are plotted in Figure 3. The time scale, plotted on the X-axis, has been normalized by dividing the elapsed time when the sample was taken, t, by the hydraulic residence time of the reactor, $\bar{t}$, which equals volume divided by flowrate. Similarly, the concentration scale, plotted on the Y-axis, has been

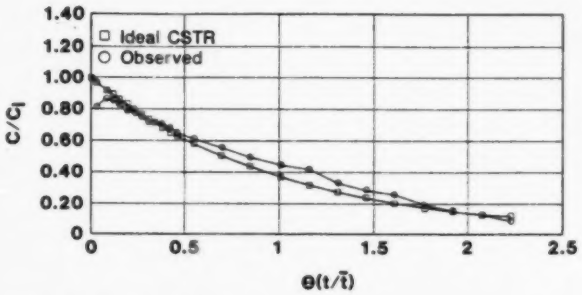

Figure 3—Step I mixing effectiveness.

normalized by dividing the sample concentration, C, by the theoretical initial tracer concentration in the reactor, C_i, assuming instantaneous mixing. C_i was calculated by dividing the total mass of tracer used by the reactor volume. The concentration of a conservative tracer in the effluent from a continuous stirred tank reactor (CSTR) can be described by the equation:

$$C/C_i = \exp(-t/\bar{t}) \quad (1)$$

The normalized concentration-time curve for an ideal CSTR for the Step I digester plotted in Figure 3 agrees closely with the measured concentrations, which indicates that Step I can be considered a well-mixed reactor.

A similar analysis for the residence time of the Step II digester at Lackawanna showed that the ideal and actual concentration-time curves matched closely except for some short-circuiting at dimensionless time less than 0.5.

During the residence time distribution study, the compressors used in the gas mixing system failed, and pumped recirculation was used for the remainder of the sampling periods to achieve digester mixing. The Step II effluent sample taken after the gas mixer failed still was close to the ideal (well mixed) relationship.

The geometric means of the performance data from Lackawanna and Hagerstown are summarized in Table 2. From the Lackawanna DDS operation and maintenance manual, the design total solids loading is 2526 kg/d with a volatile solids-to-total solids ratio of 0.63. During Phase 1B, additional solids were brought in from a nearby plant, and the volatile solids loading of 1497 kg/d approached the design value of 1591 kg/d. During the other phases of operation, the volatile solids loading was between 63 and 75% of design loading. Because of the lower solids production, Step I residence times were longer than design values listed in Table 1.

Following the expansion of DDS at Hagerstown, the design loading rate for the two process trains is 7725 kg/d with 73.5% volatile solids. The last column in Table 2 lists the total solids loading for each process train. The total DDS loading, 6216 kg/d total solids, represents 80% of the design value. The volatile solids loading, 4973 kg/d, represents 88% of the design value (5678 kg/d). Step I residence times at Hagerstown were also greater than design.

During the three, 10-week sampling periods at Lackawanna, the target Step I operating temperature was 55°C. Temperatures at the three sampling points during Phases 1, 2, and 3 are plotted in Figures 4, 5, and 6, respectively. Although the Step I geometric mean temperatures listed in Table 2 are several degrees below the goal, daily temperatures exceeded 55°C for some portion of all phases. A maximum temperature of 63°C occurred during

Table 2—Dual Digestion System operating performance.

	Lackawanna				Hagerstown	
	Phase 1A	Phase 1B	Phase 2	Phase 3	Phase 1	Phase 2
Total solids, %	4.93	5.15	4.42	6.48	6.44	7.25
Volatile solids fraction, %	63	55	69	62	78	80
Total solids loading, kg/d	1673	2722	1450	1917	3245	3255/2961[a]
Step I residence time, d	1.76	1.13	1.80	2.01	1.41	1.55/1.74[a]
Temperature, °C						
Ambient air	18.4	20.4	6.0	1.3	5.5	23.2
Step I influent	21.4	22.5	17.6	12.2	16.2	NM
Step I effluent	52.5	49.9	51.6	46.6	49.4	—[b]
Step II effluent	43.6	45.1	44.1	36.8	34.2	36.6/36.9[a]
pH:						
Step I influent	6.12	6.12	6.37	6.30	6.3	5.9
Step I effluent	7.30	7.11	7.35	7.35	6.9	6.1/NM[a]
Step II effluent	7.49	7.36	7.43	7.20	7.5	7.7/7.7[a]
Alkalinity, mg/L as $CaCO_3$						
Step I influent	1553	2016	1596	2165	NM	NM
Step I influent	2811	2932	2865	5128	NM	NM
Step II effluent	5032	4314	4038	5936	6777	8460/7318[a]
Step I oxygen feed, kg/d	582	591	636	668	NM	NM
Step II biogas production, m^3/d	293	377	—[c]	219	378	866/209[a]

Note—All values are geometric means; NM = not measured.

[a] The two values represent process train "A" value and process train "B" value, respectively.

[b] Temperature indicator was calibrated incorrectly.

[c] Recording gas meter malfunctioned.

Phase 1B. The low temperatures during Phase 3 were the result of a process upset that lasted for several weeks at the middle of the sampling period. The treatment plant staff and the system supplier could not determine a reason for the process upset. Once operation was normal again Step I temperatures climbed back to approximately 55°C toward the end of the sampling period (Figure 6).

The Lackawanna DDS was designed to operate at mesophilic temperatures in the Step I and Step II digesters. Operation of the Step I digester in the thermophilic temperature range resulted in a Step II geometric mean temperature near 44°C during Phases 1A, 1B, and 2. This temperature is between the optimum temperatures of 35°C and 54°C for mesophilic and thermophilic organism growth, respectively.[7] In the temperature range between these two values, biogas production decreased, to a minimum at 43°C. Had the system been designed for thermophilic Step I operation, additional insulation of the Step I digester and interconnecting piping would have reduced the temperature drop between Step I and Step II.

The desired Step I operating temperature at Hagerstown is between 52 and 55°C. Although the Step I temperature was less than this goal during Phase 1 (that is, prior to May 30, 1984), the temperature variability was less than that at Lackawanna. Following DDS expansion, the Step I temperature indicator was calibrated incorrectly during Phase 2. However, discussions with plant staff indicate that the desired operating temperature is currently met. The consistent Step I temperatures could be the result

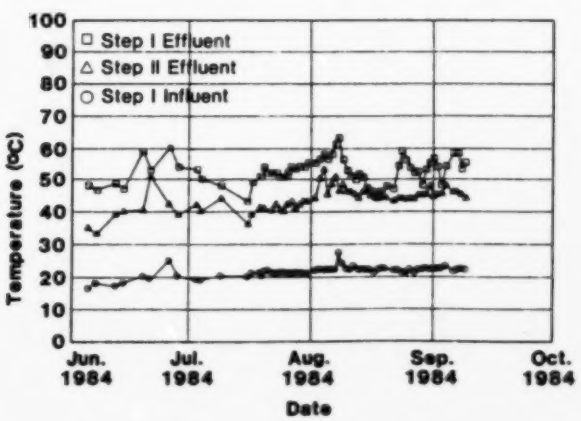

Figure 4—DDS operating temperatures–Phase 1 (Lackawanna).

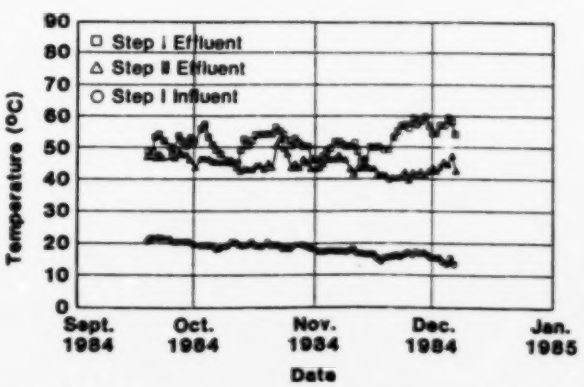

Figure 5—DDS operating temperatures–Phase 2 (Lackawanna).

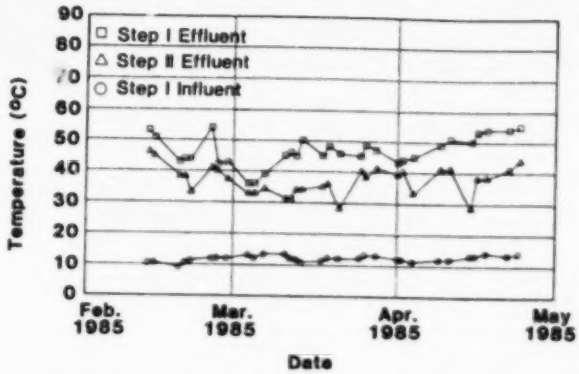

Figure 6—DDS operating temperatures–Phase 3 (Lackawanna).

of a different pure oxygen feed system used at Hagerstown. At Lackawanna, the pure oxygen feedrate is manually set and then automatically maintained as the oxygen feedrate to the pure oxygen activated sludge system varies. The resulting Step I temperatures must then be monitored to maintain the optimal oxygen feedrate. At Hagerstown, the pure oxygen feedrate is automatically controlled based on a Step I temperature feedback.

Based on pilot plant data and because the insulation of the existing anaerobic digesters at Hagerstown cannot be upgraded, heat is extracted from the sludge following Step I treatment to avoid the borderline mesophilic/thermophilic temperatures in Step II. The heat exchangers for the former first-stage anaerobic digesters were modified to circulate plant service water to cool the sludge to the optimum mesophilic digestion temperature of 35°C. This service water is circulated through the operations buildings to provide space heating. The Step II geometric mean temperatures listed in Table 2 are very close to this optimum mesophilic temperature.

Sludge conditioning for the anaerobic digestion step is accomplished when the Step I digester increases both the pH and alkalinity of the raw sludge, as shown by the Lackawanna data in Table 2. The increased buffering capacity provided by Step I treatment causes more stable Step II (anaerobic) performance. Since installation of DDS at Lackawanna, addition of buffering chemical has not been required.

To check the self-consistency of the solids data, total inert solids were calculated by subtracting the measured total volatile solids from measured total solids. Except for slight increases caused by mineralization, total inert solids should be a conservative measure through the DDS. Table 3 lists the total inert solids reductions at the two treatment plants. Thus, as a conservative constituent, total inert solids reduction should be close to zero or slightly negative. A good solids balance was calculated for Phases 1A, 2, and 3 which indicates a high degree of confidence in the measured volatile solids reductions. A poorer solids balance was calculated for Phase 1B, perhaps caused by the short sampling period relative to overall system detention time. Solids balances were much poorer during the two operating phases at Hagerstown, and were probably caused by grab samples measured only three times per week. In comparison, the solids balance at Lackawanna was calculated using measurements of daily composite samples.

The total volatile solids reductions at the two treatment plants are listed in Table 3. A minimal degree of volatile solids reduction to meet the operating temperature goal is desired to maximize the substrate available for subsequent Step II biogas production. The Step I volatile solids reductions at Lackawanna was between 13.7 and 19.9%. At Hagerstown, the Step I volatile solids reduction averaged 10.8% following DDS expansion. Overall average volatile solids reductions for both Step I and Step II at Lackawanna were between 26.9 and 44.4%. For comparison, the minimum volatile solids reduction that must be achieved for a process to be a PSRP or PFRP is 38%.[1] Reductions exceeded this value at Lackawanna during Phase 2 only. In contrast, the overall volatile solids reductions at Hagerstown were between 51.1 and 56.6%. These greater overall reductions were the result of greater solids reductions in the Step II digester, which in turn resulted from the lower, optimum mesophilic Step II operating temperatures. Step II temperatures at Lackawanna between the mesophilic and thermophilic optima probably contributed to lower Step II total solids reductions.

From the solids reductions summarized in Table 3 and the Step I oxygen feedrates listed in Table 2, the specific oxygen feedrate at Lackawanna was 3.12 kg oxygen fed per kg total volatile solids removed during Phase 1A, 2.88 kg/kg during Phase 1B, 3.19 kg/kg during Phase 2, and 3.82 kg/kg during Phase 3. The high value calculated for Phase 3, coupled with the poor performance during this period indicates decreased oxygen transfer efficiency or a lower oxygen feedrate, or both, than the instrumentation indicated. Haas[3] reported significantly lower specific oxygen feedrates of between 1.62 and 1.8 kg/kg during

Table 3—Dual Digestion System solids reduction.

	Lackawanna				Hagerstown	
	Phase 1A	Phase 1B	Phase 2	Phase 3	Phase 1	Phase 2
Total inert solids, % reduction						
Step I	6.6[a]	0.9	2.9	4.9	6.3	2.8
Step II	−14.6	16.2	−3.0	−8.1	25.9	11.5/28.1[b]
Overall	−7.1	17.0	0.0	−2.8	30.6	14.0/30.1
Total volatile solids, % reduction						
Step I	17.7	13.7	19.9	14.7	16.4	10.8
Step II	23.5	24.8	30.6	14.3	48.0	47.3/45.2
Overall	37.1	35.1	44.4	26.9	56.6	53.0/51.1

[a] Values listed are geometric mean reduction. A negative value indicates an increase across the process.
[b] The two values represent the process train "A" value and process train "B" value, respectively.

the demonstration study at Hagerstown. Although the Lackawanna mass transfer device operates at a lower power input than the Hagerstown device, similar oxygen transfer efficiencies (approximately 60% at Lackawanna and 66% at Hagerstown) were reported in previous studies when the Step I digester was operated in the thermophilic mode.[5,8]

Anomalous specific biogas production values were c. .ulated from the data at both plants, compared to an average of between 0.74 and 1.12 m^3 biogas per kg volatile solids destroyed.[9] Values at Lackawanna were between 1.18 and 1.51 m^3/kg; those at Hagerstown were between 0.22 and 0.79 m^3/kg.

Sludge dewaterability following DDS treatment, relative to the former anaerobic digestion process, could not be quantitatively evaluated. Insufficient data were available at Lackawanna to calculate the solids capture of the dewatering centrifuge during the three sampling periods. However, the minimum sludge concentration required by the landfill (20% total solids) was met with the DDS-processed sludge.

OPERATION EVALUATION

Design and construction. At both treatment plants visited for the post-construction evaluation, the DDS system was designed based on loadings provided by the plant designers. Based on subsequent experience, consideration should be given during design to the interconnecting piping and Step I digester insulation material. At Lackawanna, the concrete Step I digester is insulated by a layer of foam covered with a layer of brick. At Hagerstown, the Step I digester is simply insulated with a layer of spray-on foam insulation with an ultraviolet resistant topcoat. Based on conversations with treatment plant personnel, no extraordinary problems were encountered during DDS construction at either facility.

Major equipment requirements. DDS requires few pieces of equipment in addition to those required for conventional anaerobic treatment. The major item is an oxygen source. A PSA oxygen generation system was already included in the plant design at all three locations to supply the requirements of the pure oxygen activated sludge process. An incremental increase in the PSA system capacity was provided to accommodate addition of DDS to the plant design. Although the ability to use air for autothermal, thermophilic aerobic digestion has been demonstrated,[10] the use of high-purity oxygen in the DDS system has several advantages. First, it provides a greater driving force for mass transfer, which results in a faster oxygen dissolution rate. Second, lower gas flowrates reduce the amount of heat lost from the digester contents.

The second major piece of equipment required by DDS is a mass transfer device to achieve efficient oxygen transfer in the Step I digester. This is a motor-driven, slowly rotating (25–32 rpm), custom designed vertical shaft that extends the depth of the digester with four pairs of tapered arms designed to shear the rising oxygen bubbles. Baffles are mounted to the side of the digester, with notches for the tapered arms to pass through. This equipment, fabricated of stainless steel, was developed based on experience during the full-scale demonstration project at Hagerstown.[5]

The mass transfer device introduces a question of mechanical reliability into the DDS. The purpose of the DDS mass transfer device is to shear the rising gas bubbles. In June 1985, the mass transfer device at Lackawanna was taken out of service because the motor was drawing higher currents than previously measured and had tripped off several times. The digester was shut down and drained for inspection. The long overhung central vertical shaft of the mass transfer device was out of plumb by nearly 31 cm at the bottom. Solids concentrations in the digester greater than twice the design concentration were detected following major rainstorms and may have contributed to this problem. Repair required that the 7.3-m shaft be removed, which put the digester out of service. Subsequent inspection of the mass transfer gear reduction box and bearings indicated no problems with these components.

Several options are available to mitigate the potential mechanical problems. Another bearing can be included at the bottom of the digester where the end of the shaft is inserted to reduce potential motion of the bottom of the shaft. This has not been included in designs because of maintenance difficulty and the fact that only one out of the five shafts currently in service has experienced problems. To provide some degree of redundancy, the total design volume of the Step I digester can be split between two digesters, as at Nutbush Creek. Two sets of mechanical equipment would incur additional costs, but for facilities where autoheating in Step I is the only means of raising the sludge temperature for anaerobic digestion, the additional reliability is necessary. At Lackawanna, the old anaerobic digester heat exchangers were left intact during modification and were used to provide conventional mesophilic digestion during Step I repair.

Process operation and control. According to treatment plant personnel, the DDS process is simple to operate. Compared to conventional anaerobic digestion, only one additional sample point is required for process monitoring and no additional laboratory equipment is necessary. Oxygen feedrate is directly related to the Step I operating temperature and is the main process control variable. The raw sludge pumping rate depends on solids production as well as the thickening process to maintain a total solids concentration of approximately 5%. The design of a consistent sludge thickening process is important to the performance and ease of DDS operation.

Because of lower solids production at startup compared to ultimate design values, one suggested improvement is to provide for greater control over the liquid level in the Step I digester. This would allow 1-day detention times to be maintained at lower sludge production rates.

During the 2.5 years that DDS has operated at Lackawanna, several modifications have been made to the system to improve operation. These include:

- Step I odor scrubbing system;
- Telescoping valve air-purge;
- Gas engine intake manifold and clutch replacement;
- Gas engine low-speed cutoff switch;
- PSA oxygen generation totalizer;
- DDS oxygen feed totalizer;
- DDS automatic feedrate control; and
- Lower explosive limit (LEL) meter sensing head relocation and replacement.

Current DDS design reflects the modifications to the system as originally installed at Lackawanna.

In an earlier study at Lackawanna when the Step I digester was operated in the thermophilic mode and Step I headspace gasses were vented to the atmosphere for gas flowrate measurement, odor complaints were received from the surrounding res-

idential area. The external valve pit at the top of the digester, into which heated sludge discharges through the telescoping valve, was originally designed to be covered with open grating. To prevent similar complaints during this study, a steel cover and odor scrubbing cannister were designed for the valve pit. At Hagerstown, an odor scrubbing cannister, a commercially available 0.21-m^3 drum prepacked with granular activated carbon, was installed at the time of construction on each of the two Step I digesters. Because of the limitations of getting that size unit to the top of the Lackawanna Step I digester, a custom odor scrubber was designed with a 0.11-m^3 stainless steel drum packed with granular activated carbon, available in bulk. Stainless steel was used to resist corrosion from condensation of the warm, moist vent gasses. The odor scrubbing unit is visible on the top left of the Step I digester in Figure 1.

To solve clogging problems of the effluent piping and the telescoping valve controlling the Step I digester level at Lackawanna, the operators installed a compressed air line at the bottom of the valve. The clogging may partially be caused by incorrect installation of the effluent piping. Although this helps to unclog the valve, operator attention is required to verify that flow is maintained.

Because there are no sludge heating requirements for the Step II digester, the availability of biogas for use elsewhere in the plant results in use of equipment not commonly found at smaller wastewater treatment plants, such as a gas engine or gas scrubber. At Lackawanna, the biogas is used in a gas engine used to drive the PSA compressor. During the special study, several problems prevented use of the engine. First, the manifold piping was sized incorrectly and caused too great a headloss for the gas pressure provided by the floating cover storage. Second, the clutch between the gas engine and the electric motor, normally used to drive the compressor, failed during testing. Both problems have been corrected by replacing the manifold piping and installing a heavy-duty clutch. A low-speed cutoff switch was also installed to stop the motor from idling at low rpm when the biogas pressure dropped too low. By early July 1985, the gas engine was operational.

However, when sufficient biogas is not produced for continuous engine operation, a cost estimate modification should be made for future gas engine estimates based on manufacturer's suggested operating procedure for intermittant operation. According to the manufacturer the gas engine should be run on natural gas for 1 hour before and 1 hour after a period of biogas operation to reduce corrosion. Besides increasing fuel costs, the increased run time reduces the service interval. At Lackawanna, where the gas engine is able to operate on biogas for about 13 to 14 h/d, the service interval would be reduced by approximately 14 to 15%.

A LEL meter was included in the Step I control panel to monitor for dangerous levels of flammable gasses in the high percentage oxygen headspace of the covered reactor. Condensation of vapors from the headspace gas and subsequent corrosion necessitated replacement of the LEL meter sample pump and sensing heads at Lackawanna. To prevent the need for future replacement, the LEL meter sensing head is now housed in an environmentally sealed, heated enclosure on top of the Step I digester. The sampling pump was eliminated by taking the headspace gas sample from the vent return to the pure oxygen activated sludge process. A condensate trap in the sample line prevents any condensation from reaching the sampling head.

As discussed above, the oxygen feedrate to the Lackawanna Step I digester is manually set, but varied with changes in oxygen demand from the pure oxygen activated sludge system. Retuning the control system to maintain a constant feed pressure solved this problem. Totalizers are planned to be installed on the oxygen lines coming out of the PSA system and going into the Step I digester, making it easier to directly measure PSA production and DDS consumption.

COST EVALUATION

Cost estimates prepared during preliminary design were available for Lackawanna. Actual construction costs were obtained where available for the two treatment plants visited for the post-construction evaluation. Because DDS was constructed as a modification to existing two-stage anaerobic digestion at Lackawanna and Hagerstown, the construction costs are approximate. During the special study at Lackawanna, actual power consumption of the components of DDS was measured and operation costs calculated.

Estimated costs. Estimated capital, operation, and maintenance costs for the DDS system at Lackawanna were available from the preliminary design report. The present worth values are summarized in Table 4. In comparing the present worth of the innovative/alternative process, DDS, to the most cost effective conventional process, two-stage anaerobic digestion, a cost preference is given to the innovative/alternative process. Because of the higher risk in using innovative/alternative technologies, the present worth of the conventional technology is adjusted to reflect a willingness to accept a higher cost for a potentially promising technology. The adjusted present worth of the conventional technology is calculated by adding 115% of the present worth of the design components replaced by the innovative/alternative technology to the present worth of the non-replaced

Table 4—Preliminary DDS cost estimate at Lackawanna.

	Dual digestion system		Conventional two-stage anaerobic digestion	
	Yearly cost	Present worth	Yearly cost	Present worth
Capital cost[a]	—	$1 002 715	—	$818 600
Labor	$76 462	836 568	$67 809	741 888
Power	1 992	21 799	2 292	25 081
Chemicals	—	—	1 141	12 479
Maintenance and spare parts	—	130 026	—	151 200
Digester heating	—	—	4 162	45 538
Digester gas for space heating	(−10 488)	(−114 752)	—	—
Total present worth		$1 876 356		$1 794 786
Present worth adjusted for 115% cost preference[b]		—		$1 939 948

[a] Estimated *Engineering News Record* Construction Cost Index of 3355.
[b] Present worth of non-replaced conventional processes plus 115% of present worth of replaced conventional processes.

components. To meet the cost effectiveness criteria for increased federal funding, the present worth of the innovative/alternative process must be less than the adjusted present worth of the conventional process. In the cost effectiveness analysis for Lackawanna, a 3.4% cost savings for DDS was projected.

The capital costs for the oxygen generation system represent only the incremental costs for increasing the PSA system capacity from 2 to 3 T/d. The costs for a stand-alone, 1-T/d oxygen generation system would be sufficient to eliminate the DDS cost advantage shown in Table 4.

However, a true comparison of costs must follow the classification of DDS as a PSRP or PFRP. If DDS is classified a PSRP, a direct cost comparison to conventional anaerobic digestion is valid because the two processes would provide equivalent treatment. However, if DDS were classified a PFRP, a direct comparison would not be reasonable because a higher level of treatment would be achieved and a greater number of ultimate sludge disposal options would be available.

Actual costs. Actual construction costs for the installation of DDS at Lackawanna, including Step II modifications, were estimated from the contractor payment records. The total construction cost was approximately $1 318 480. Of this total $484 000 was the construction cost for the Step I digester. Escalating the design estimate of $1 002 715 to the midpoint of construction (October 1982), the total construction cost was 13.1% higher than the design estimate. At Hagerstown, the construction cost for the additional Step I digester was approximately $650 000. Based on the design total solids loading rates, the Step I construction costs were $191 · d/kg at Lackawanna and $168 · d/kg at Hagerstown.

Operation costs for DDS were difficult to determine. Budgets for electrical power, labor, and chemicals at each of the two plants visited during the post-construction evaluation were not broken down process by process. To obtain some better estimates for some of the costs associated with DDS operation, measurements were made of electrical power consumption by the major pieces of electrical equipment. The results are listed in Table 5.

An amp meter was used to measure the electrical current drawn by the PSA fin fan cooler, and Step I mass transfer device. The current drawn was compared to the full load current listed on the motor nameplate. The ratio between actual and full load current was multiplied by the full load shaft horsepower and by the efficiencies listed in the table to calculate the electrical power (kW) demand. An estimate of yearly run-time was used to calculate energy consumption.

Performance tests of the PSA system were used to calculate the energy consumption of this component. For the 2-week thermophilic operation period analyzed, the PSA production at Lackawanna averaged 76% of the maximum production of 2727 kg/d. The PSA energy consumption attributed to DDS was calculated using the fraction of oxygen fed to DDS during this period, 32.2%, and the oxygen transfer efficiency, 60%, as determined in a previous study.[8] At Lackawanna, the oxygen not used in the Step I digester is vented to the pure oxygen activated sludge reactors, so the DDS energy consumption is based on oxygen actually used in Step I. At the plant's electrical cost of $0.061/kWh, the DDS yearly electrical cost is $14 270.

In contrast, the DDS energy consumption at the other two plants would have been calculated based on oxygen fed to the Step I digester, because the headspace gasses are vented to the atmosphere. To minimize the quantity of oxygen fed, the mass transfer devices at these two plants are operated at 32 rpm to maximize oxygen transfer.

Using the gas engine manufacturer's design information, the electrical cost savings achieved through gas engine use at current biogas production rates were calculated. The results are listed in Table 6. At the current average biogas production of 293 m^3/d measured during Phase 1A, the gas engine could be run approximately 13.0 to 14.3 h/d, or 54 to 60% of the time. At the total power requirement of the PSA compressor of 359 510 kWh, which represents oxygen supplied to both DDS and pure oxygen activated sludge, annual power savings will be between approximately $11 842 and $13 158.

CONCLUSIONS

Performance data evaluation and site visits to the three treatment plants in the U. S. using the dual digestion system for sludge stabilization demonstrates that this technology is a promising process alternative and is especially attractive to those plants that use pure oxygen activated sludge. The DDS, which was funded at an increased level at these three plants through the EPA Innovative/Alternative Technology program, can achieve solids reductions high enough (>38%) to be classified as either a PSRP or PFRP. Classification in the latter group allows a greater number of ultimate disposal options on cropland because of greater pathogen destruction. Available cost data show DDS costs to be comparable to those for two-stage mesophilic anaerobic digestion, a PSRP. If DDS is classified a PFRP, a higher level of treatment may be achieved for equivalent costs. The

Table 5—Measured DDS power consumption at Lackawanna.

Component	Nameplate rating	Measured current draw (A)	Shaft power (kW)	Efficiency[a]	Line kW	Run time (h/a)	Energy (kWh)
PSA compressor[b]	93.2 kW at 126A	—	—	—	41.0	8700	359 510
PSA fin fan cooler	3.7 kW at 6.8A	5.9	3.2	0.835	3.9	8760	33 940
Step I mass transfer device	14.9 kW at 25A	23.1	13.8	0.865	15.9	8760	139 560
Step II gas recirculation	2.2 kW at 4.9A	3.7[c]	1.7	0.80	2.1	8760	18 370
							Total = 233 945[d]

[a] From General Electric table for Type K motors (NEMA Design B).

[b] From PSA performance testing operating at approximately 75% of maximum capacity.

[c] Assumed.

[d] Power consumption by PSA compressor and fin fan cooler adjusted because DDS only uses 32.2% of oxygen generated by PSA with a 60% transfer efficiency with Step I in thermophilic mode.

Table 6—Predicted savings from digester gas utilization at Lackawanna.

Digester Gas Characteristics
65–70% CH_4
Lower heating value of CH_4 = 34kJ/L
Lower heating value of digester gas = 22.1–23.8 kJ/L (MJ/m^3)
Gas Engine Fuel Consumption
Fuel consumption range is 11.84 to 12.16 MJ/kWh
At annual PSA energy consumption of 359 510 kWh, fuel requirement is between 4 256 600 and 4 371 600 MJ/a
Calculated digester gas consumption is between 20.42 and 22.58 m^3/h
Digester gas production during Phase 1A was 293 m^3/d
Can run engine approximately 13.0 to 14.3 h/d (54–60% of the time)
Cost Savings
Total PSA compressor electrical costs = (359 510 kWh) ($0.061/kWh) = $21 930/a
Projected savings of between 54 and 60% or $11 842–$13 158

decision of DDS classification rests with EPA, who must evaluate pathogen reduction data for this process.

Based on interviews with treatment plant staff, DDS is easy to operate and requires no significant additional labor beyond that for anaerobic digestion. Temperatures in the 1-day detention time, pure oxygen aerobic first stage reactor, are controlled by varying the pure oxygen feedrate. The pH and alkalinity of the sludge increases following first stage treatment, which conditions the sludge for subsequent anaerobic digestion in an 8-day detention time digester. Chemical addition to maintain an optimal pH range for anaerobic digestion has not been required.

However, there are some performance and mechanical reliability problems based on several years of operation at these three plants. Variable degrees of performance were noted at one of the two plants where data were available. Although temperatures reached target thermophilic levels and solids reduction exceeded the goal, consistent, long-term performance was not demonstrated at one of the plants. Performance was acceptable at the other plant. These differences may be caused by varying sludge quality after thickening, differences in DDS design and control between the two plants, or process operation. The other issue is mechanical reliability of the process. Apparent mechanical failure of the mass transfer device in the first stage digester caused a shutdown on this digester so that the central shaft could be straightened. As autoheating of the sludge in the aerobic step is the means used to heat the sludge for subsequent anaerobic digestion, the reliability of the aerobic step must be increased to an acceptable level in subsequent designs.

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